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In-Service Monitoring of Structures

Surveillance des constructions en service

Ueberwachung bestehender Bauwerke

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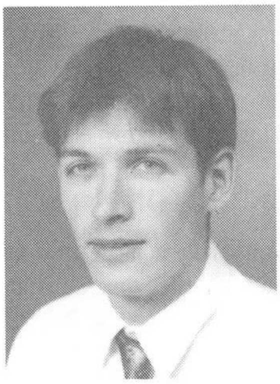

Richard Moss, born 1963, obtained his first degree at Sussex University and his PhD from Imperial College, London University. During a period of 10 years at BRE his research has concentrated on load testing and structural monitoring, although he has also carried out general appraisal work.

SUMMARY

This paper addresses the subject of monitoring of structures on a philosophical basis. Issues addressed include reasons for installing a monitoring scheme, problems associated with monitoring schemes, methods of monitoring and instrumentation. The paper briefly describes methodologies for effective instrumentation deployment based on concepts of robustness and vulnerability. Different monitoring techniques and in particular the advantages and disadvantages of visual and manual methods vis-a-vis autonomous systems are also discussed.

RÉSUMÉ

L'article traite de la surveillance des structures du point du vue philosophique. Parmi les sujets abordés, il y a lieu de citer les raisons qui poussent à installer un système de surveillance, les problèmes associés aux-dits systèmes, les méthodes de surveillance et l'instrumentation. Il donne en outre un bref descriptif des méthodologies utilisées pour un déploiement efficace de l'instrumentation en se basant sur les concepts de robustesse et de vulnérabilité. Y sont également traitées les différentes techniques de surveillance, en mettant en particulier l'accent sur les avantages et les inconvénients que présentent les méthodes visuelles et manuelles vis-à-vis des systèmes autonomes.

ZUSAMMENFASSUNG

Dieses Referat behandelt das Thema Überwachung von Bauwerken auf philosophischer Basis. Unter anderem werden folgende Fragen in Erwägung gezogen: Gründe für die Installation eines Ueberwachungsplans, mit Ueberwachungsplänen verbundene Probleme, Methoden zur Überwachung und Instrumentarium. Das Referat beschreibt in kurzen Zügen die Methoden des wirksamen Instrumenteneinsatzes auf der Basis der Konzepte der Robustheit und der Verletzbarkeit. Verschiedene Ueberwachungsverfahren und insbesondere die Vorteile und Nachteile von visuellen und manuellen Systemen im Vergleich zu autonomen Systemen werden ebenfalls besprochen.

1. INTRODUCTION

1.1 There are an increasing number of buildings that require informed decisions to be made about their continued safety and serviceability. The approach adopted to the design of structures has traditionally been the performance of calculations to justify the adequacy of the proposed construction in accordance with codes of practice. Assumptions are made as to the loads to which structures are subjected and the structure's behaviour.

1.2 The structure is considered at different hierarchical levels - typically the performance of individual elements and frame assembles - with assumptions made concerning the boundary conditions applicable, coupled with consideration of overall behaviour (eg ensuring structural stability). Such an approach has been necessitated by the fact that most structures are 'one-offs' and it is not feasible to codify for individual structures. However with technological developments in the fields of monitoring instrumentation, data logging and software, consideration of the actual as-built performance of individual structures and classes of construction is becoming a realistic possibility.

2. REASONS FOR INSTALLING A MONITORING SCHEME

2.1 There may be many reasons for employing a structural monitoring system and these will generally dictate the length of time over which the monitoring system is required to function. Depending on the reasons for installing the monitoring system it may be installed during or subsequent to construction. For monitoring equipment installed subsequent to construction there may be clearer and more direct objectives which can be set for the monitoring scheme. This is because in such cases the monitoring system will usually be installed to address specific problems identified with the structure.

2.2 It is obviously crucially important that the equipment used to monitor the response of the structure is suitable. Different types of equipment are likely to be needed for structures whose response is predominantly dynamic rather than static in nature.

2.3 Supplementary to the basic concept of monitoring the structure, there is the idea of testing the structure at regular intervals to check for changes in the response. It is advocated that such testing can give early indication of structural degradation.

2.4 Since measurements of load are difficult to make directly, static load testing potentially has a useful rôle to play in the initial calibration of the monitoring system, thereby providing a benchmark against which the results of subsequent monitoring of the structure in service can be assessed.

3. PROBLEMS ASSOCIATED WITH MONITORING SCHEMES

3.1 In devising any monitoring scheme the first step is naturally to define the objectives and purpose of the monitoring scheme. Considerable thought needs to be given to the information required and the appropriate instrumentation. Presentation and storage of the information is also important, and consideration needs to be given to what the data collected will be used for.

3.2 For economic reasons it is not feasible to instrument the whole of a structure and a rational basis is required for selection of positions to monitor which represents the worst case within a structure. Approaches to this problem are considered further in Section 6.

3.3 For long-term monitoring (ie over many years) the reliability and stability of the instrumentation used is of crucial importance. It is necessary to identify the parameters which it is desirable to measure and the most appropriate instrumentation to use for measuring these parameters. Types of instrumentation which may be suitable are described further in Section 5.

4. ADVANTAGES AND DISADVANTAGES OF VISUAL AND MANUAL METHODS

4.1 Manual methods have relatively low initial set-up costs compared to automatic or autonomous systems, but incur relatively high repetitive costs each time a set of measurements is taken. Accordingly manual methods are likely to be employed when either the programme of monitoring is expected to be short and involve only a limited amount of instrumentation, or where monitoring of a limited number of instruments will take place over a longer time-scale with repeat measurements taken infrequently.

4.2 The economic balance between automatic / autonomous and manual data collection methods is constantly changing. Technology continues to enhance the sophistication of instrumentation and data logging equipment, whilst reducing their cost in real terms. Many automatic systems can be controlled remotely via a modem and this can reduce the need for periodic visits to site.

5. INSTRUMENTATION

5.1 The instrumentation considered here is in general restricted to that which is capable of being incorporated within data logging systems so that measurements can be taken automatically and remotely.

5.2 Instrumentation for monitoring of structural behaviour can be categorised broadly into instrumentation which measures actions on the structure (eg imposed loads, wind loads and temperature changes) and that which measures the response of the structure to those actions (eg deflections, vibrations, rotations, strains and resultant stresses).

5.3 The need for dynamic capability of the instrumentation is governed by the anticipated behaviour of the structure (ie whether predominantly static or dynamic in nature), and is principally related to the type of structure being considered. Dynamic actions and responses will need to be measured for bridges and offshore structures but not for most buildings. Other structures and structural elements likely to exhibit a dynamic response include long-span floors, masts and chimneys.

5.4 Direct measurement of loads is usually achieved using load cells. Because of the high dead load component in structures, small changes in load require to be resolved against a background of high standing load. This calls for a high degree of resolution and hence stability of the instrumentation. Of the different types of load cell available, vibrating wire load cells have better long-term stability than load cells with electrical resistance strain gauge elements.

5.5 Installation of pressure transducers on the ends of pressure tappings can allow direct measurements of wind pressures on the elevations of buildings. This has been done extensively for small-scale models tested in wind tunnels and more recently at full scale [1]. Pressure transducers measure pressure difference, not absolute pressures. For this reason a static probe is needed to allow a reference pressure to be established against which other pressure measurements can be compared.

5.6 Pressure transducers are normally used in conjunction with an anemometer to measure wind velocity. The anemometer can be used to control the logging process by triggering logging of the transducers only when a minimum threshold velocity is reached.

5.7 Of the different types of device available for measuring temperature, thermocouples are generally considered to be the most suitable. Although not as accurate as some other types of temperature measurement device, they are likely to be sufficiently accurate for most structural monitoring purposes.

5.8 The type of instrumentation most suitable to monitor long-term deflections of structures will depend on a number of factors such as the accuracy with which measurements are required to be made, the accessibility of the positions where movements are required to be measured, and the ease of providing a fixed frame of reference.

5.9 Where a frame of reference can be established reasonably easily for individual measurement points, the simplest method of measuring displacements is to use displacement transducers. These are usually either of resistive or inductive type design, being termed potentiometers or linear variable differential transformers (LVDT's).

5.10 Where a frame of reference cannot easily be established, other techniques such as use of hydraulic levelling systems and lasers could be adopted. The choice between these two is likely to depend on factors such as the visual access of the positions at which measurements are required to be made and the distances involved.

5.11 Where the installation of a reference frame is not possible or would be obtrusive, an alternative method of deriving deflections is to measure slope and integrate to calculate deflection.

5.12 Perhaps the most promising device for measuring rotation for the purpose of long-term monitoring is the electrolevel. Electrolevels can be made waterproof, and this makes them particularly suitable for use in hostile environments. However electrolevels are not appropriate for taking dynamic measurements and can be adversely affected by variations in temperature.

5.13 The vibration measurement device most suited to long-term monitoring applications is generally considered to be the geophone. This is a relatively cheap and robust device and does not need separate amplification and signal conditioning equipment. However geophones are generally not as accurate as accelerometers.

5.14 The two types of device commonly used for measuring strain are vibrating wire strain gauges and electrical resistance strain gauges. Electrical resistance gauges do not have as good long-term stability as vibrating wire gauges.

5.15 The instrumentation considered above is suitable for incorporating within a data logging system. Such a system becomes essential when the instrumentation needs to be read remotely and a large number of instruments require to be read within a relatively short time span. It is also necessary to have an autonomous system where alarms are to be activated automatically when threshold values are exceeded.

5.16 Distributed data acquisition systems have advantages over more conventional data logging systems for use in structural monitoring, particularly for large structures, because of the savings in cabling requirements. Distributed systems also allow the logging device to be located in the proximity of the instrumentation and this can be important to preserve signal quality.

6. METHODOLOGIES FOR EFFECTIVE INSTRUMENTATION DEPLOYMENT

6.1 BRE has been considering methods for deciding which parts of structures should be monitored, since it will not be possible to instrument a whole structure and a rational basis is required for deciding which parts of a structure to instrument. In many cases this will be determined by logistical constraints, in terms of which parts of the structure are accessible and where installation of instrumentation is acceptable aesthetically. However it is still useful to have a theoretical basis for deciding optimum instrumentation deployment.

6.2 With this in mind, BRE has let a contract to look at the possible application of vulnerability theory to this problem.

6.3 The emphasis of structural vulnerability analysis is not the usual one of analysing a structure under some given loading condition. Rather it is to examine the vulnerability of a structure to any possible loading action. This is accomplished by examining the quality of well-formedness of what are termed structural rings at various levels of definition within a structure, and those rings which are the most vulnerable or critical together with the actions which might cause failure.

6.4 A structural ring is a load path which is capable of resisting an arbitrary set of applied forces. A structure can then be represented at various hierarchical levels of definition in terms of clusters of interconnected structural rings.

6.5 The well-formedness of a structural ring is a measure of its ability to resist loading from any arbitrary direction. The well-formedness depends on the orientation and stiffness of the members within the ring and the stiffness of the joints connecting the members in the ring.

6.6 Vulnerability theory thus considers the geometric layout of the structure under consideration and homes in on the most critical elements within the structure.

6.7 It is intended to apply the methods described above to predict where instrumentation should be installed in structures which are to be monitored in the field.

7. MONITORING OF STRUCTURES IN THE FIELD

7.1 The Section in which the author works has been involved in the monitoring of a number of structures in the field. However the structure with which the author has had particular involvement is known as the Swaminarayan Hindu Mission Complex and is in Neasden, NW London.

7.2 The aims behind monitoring this particular structure, and hopefully others in the future, are principally to gain a better understanding of the behaviour of structures in service and the loads to which they are subjected.

7.3 In deciding which parts of the structure to monitor, design drawings were considered detailing the various forms of construction and materials used. The main part of the structure comprises an assembly hall comprising an outer steelwork frame and a series of long-span trusses giving clear spans of 45 m. Adjacent to the assembly hall are areas constructed in reinforced concrete.

7.4 Initially it was decided that it would be interesting to carry out the following :

1. Instrument the main steelwork frames - measure loads in columns, deflections of beams and loads / strain in bracing members.
2. Measure loads in reinforced concrete columns.
3. Measure deformations of both ribbed and solid reinforced concrete slabs.
4. Instrument the steelwork trusses - measuring loads / strains in the top and bottom chords near the centre, and diagonal members near the ends of the trusses. If feasible measure the overall deflections of the trusses.

7.5 In the event financial and other constraints limited the amount of instrumentation that could be installed and concentration was placed on monitoring the steelwork trusses.

7.6 Two out of a total of seven main trusses were instrumented, the decision on which trusses to instrument being governed by the loading likely to be seen by these particular trusses in service. As the trusses were symmetrical it was decided to measure the outer fibre strains in the most heavily stressed members in one half of each truss only. This was achieved using vibrating wire (VW) strain gauges (total 8 gauges per truss).

7.7 It was not practicable to measure the deflections of the trusses directly and in an attempt to measure the deflections in service a series of electrolevels was installed on the bottom chord of each truss. These devices measure rotation and in deriving deflections the slope measurements have been integrated assuming local / secondary bending effects between node positions can be ignored.

7.8 Wiring from all the instrumentation on each truss is fed back to a single data collection point and the intention is to install a data logger with a modem link so that data from all the instrumentation can be accessed remotely via a telephone line.

8. CONCLUSIONS

1. There are an increasing number of buildings that require informed decisions to be made about their continued safety and serviceability. With technological developments in the field of monitoring instrumentation, data logging and software, consideration of the actual as-built performance of individual structures and classes of construction is becoming a realistic possibility.

2. There may be many reasons for employing a structural monitoring system and these will generally dictate the length of time over which the monitoring system is required to function.

3. For monitoring equipment installed subsequent to construction there may be clearer and more direct objectives which can be set for the monitoring scheme. This is because in such cases the monitoring system will usually be installed to address specific problems identified with the structure.

4. For economic reasons it is not feasible to instrument the whole of a structure, and a rational basis is required for selection of positions to monitor which represents the worst case within a structure. Approaches are described which may enable such positions to be determined.

5. Manual methods of monitoring are likely to be employed when only a limited amount of instrumentation is involved and a limited number of measurements is to be taken. An autonomous system is necessary when the instrumentation is required to be read remotely or alarms are to be activated automatically when threshold values are exceeded.

6. Distributed data acquisition systems have advantages over more conventional data logging systems for use in structural monitoring, particularly for large structures.

7. Monitoring appears to have an important rôle to play in the management of structures and potentially extending their useful life. This is particularly so given developments in data handling and interpretation methods which are occurring.

9. REFERENCE

1. ROBERTS A P and GLASS A G, The Silsoe Structures Building - Its Design, Instrumentation and Research Facilities. AFRC Inst Engng Res, Silsoe, UK, Div Note DN 1482, Oct 1988.